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54 Method for growing a single crystal of compound semiconductor.

67 Highly impurity doped single crystal often suffers from impurity precipitation. The cause of the occurrence of impurity precipitation is supposed to be the supercooling. To avoid the occurrence of supercooling the pulling speed is slowly lowered during the crystal growth in the LEC methods. The beginning of the occurrence of impurity precipitation is delayed by lowering the pulling speed. Additional application of magnetic field is more effective.

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METHOD FOR GROWING A SINGLE CRYSTAL
OF COMPOUND SEMICONDUCTOR

DESCRIPTION

5 This invention relates to an improvement
of a method for growing a single crystal of compound
semiconductor.

Compound semiconductor has various kind
of compositions — GaAs, InP, InAs, GaP, InSb, etc.
Among the components the element of group V has a
10 high dissociation pressure. It is difficult to grow
a stoichiometric single crystal because of this high
dissociation pressure of the element of group V.

An LEC (Liquid Encapsulated Czochralski)
method is one of most preferable methods for growing
15 a single crystal of compound semiconductor. The LEC
method has advantages that circular wafers are easily
obtained and semi-insulating GaAs single crystal is
grown without doping Cr etc. It is an excellent
method from the industrial viewpoint.

20 The LEC method has many improved variations.
However there are some inherent disadvantages in
conventional LEC methods.

In all LEC methods a single crystal is
pulled up using a seed crystal from a melt of compound

semiconductor covered with a liquid encapsulant under an inactive gas pressurized at several atm to several tens atm to prevent the element of group V from escaping.

5 When the single crystal emerges from the liquid encapsulant, it is rapidly cooled by a vehement convection of inactive gas above the liquid encapsulant. Strong thermal stresses occur in the rapidly cooled crystal, which result in many lattice defects in the crystal.

10 An ingot grown by the LEC method is sliced into many thin wafers. The wafers are etched. Then etch pit density (EPD) is measured. The EPD of the wafers sliced from the LEC-grown crystal is about $10,000/\text{cm}^2$ to $100,000/\text{cm}^2$.

15 Many improvements of LEC methods have been proposed to overcome the disadvantages of conventional LEC methods.

20 One proposal is an idea of preventing the generation of strong temperature gradients in a cooling single crystal. For this purpose the cooling by the convection of the inactive gas must be suppressed.

25 To suppress the cooling, the thick liquid encapsulant seems to be effective. Namely instead in gas a single crystal is slowly cooled in a thick liquid encapsulant instead of an inactive gas.

The liquid encapsulant plays a role as heat-insulator. However this method consumes great amount of liquid encapsulant. Because the single crystal rotates in the liquid encapsulant with a high viscosity, it is
5 difficult to control the diameter of single crystal. Although this proposal is able to be put into practice, it has these disadvantages.

Another proposal is to alleviate the temperature gradients by using plural heaters.
10 This improvement may be called " multi-heater method ". More than two heaters and heat-insulators are installed along a vertical direction to alleviate the vertical temperature gradient.. Rising in a moderate temperature gradient, a single crystal is slowly cooled. The
15 purpose of the improvement is to heighten the thermal uniformity in the space above the liquid encapsulant.

Third proposal is an idea of doping isoelectronic impurities. Isoelectronic impurity is one which has the electronic property same as the
20 component elements of crystal. In the case of III-V compound semiconductor, isoelectronic impurity is one of the element of groups III and V except the components.

For example, In, B, Sb, Al, P etc., are
25 isoelectronic impurities for GaAs.

If some isoelectronic impurities are doped with more than 10^{18} atoms/cm³, the EPD of the doped crystal is reduced to a great extent. Doping of other isoelectronic impurities are of no use.

5 For example for GaAs single crystal, the isoelectronic impurities In, Sb and B are effective to reduce the EPD.

10 However the reason why the isoelectronic impurities reduce EPD has not been clearly explained yet.

Distribution coefficient is defined as a quotient of an impurity concentration in solid divided by an impurity concentration in liquid or melt when the solid phase and the liquid phase are in equilibrium.

15 For example, the distribution coefficient of In in GaAs is 0.1 to 0.15.

20 To dope In to a crystal, the GaAs melt from which the crystal is pulled must include In at six to ten times as much as the prescribed concentration in a crystal.

25 While a single crystal is pulled up from a melt including a high impurity concentration, the impurity concentration in the melt is increasing, if the distribution coefficient of the impurity is less than 1.

5 If In concentration is $5 \times 10^{18}/\text{cm}^3$
at the front portion of a GaAs crystal grown by an
LEC method, In concentration would attain to higher
values at middle portion or back portion of the
crystal.

High impurity concentration brings about
impurity precipitation. The portions including
impurity precipitation cannot be used as substrates on
which semiconductor devices are fabricated.

10 The improved LEC method to dope an
impurity to reduce EPD must face with the new
difficulty——impurity precipitation .

15 If the impurity concentration in melt is
high, impurity precipitation appears at an early
stage. If the impurity concentration is low, EPD can
not be reduced enough, although the beginning of
precipitation delays.

Why does the impurity precipitation
occur ? This has not been solved yet.

20 The beginning of impurity precipitation
depends not only on the impurity concentration in
melt but also the pulling speed. Pulling speed is
defined as a vertical speed of an upper shaft.
The seed crystal as well as the growing crystal are
25 pulled by the upper shaft. Then the pulling speed
is equivalent to the growing speed in case of LEC
methods.

In general the smaller pulling speed delays more the beginning of impurity precipitation.

The multi-heater method, one of improved LEC methods, cools a growing crystal in a quasi-
5 uniform thermal environment with a very low temperature gradient to reduce thermal stress. However this improvement seems to advance the beginning of impurity precipitation.

Two improvements of LEC methods to
10 reduce EPD — doping of isoelectronic impurity and cooling in low temperature gradient — make the impurity precipitation problem more serious.

As mentioned before, low pulling speed delays the beginning of precipitation. However if
15 a single crystal was pulled up at a constant low speed, the crystal growth would take much long time. It is undesirable from an economical viewpoint.

Considering the fact that the beginning of precipitation depends not only on the impurity
20 concentration but also on the temperature gradient and the pulling speed, this inventors suspected that the cause of impurity precipitation might be "super-cooling".

When a liquid is cooled, it becomes a
25 solid at a freezing point (melting point) in

general. However if cooling rate is low enough,
the liquid state is kept below the freezing point.
This phenomenon is called supercooling.

5 The condition for occurrence of
supercooling in a Czochralski method has been already
considered.

The condition for occurrence of super-
cooling is given by

$$\frac{G_{\ell}}{R} < \left(\frac{G_{\ell}}{R} \right)_c K_e \quad (1)$$

10 where K_e is an effective distribution coefficient,
 G_{ℓ} is a temperature gradient in melt near a solid-
liquid interface, and R is a growth rate (i.e. a
pulling speed). The round bracket suffixed with c
signifies a critical value of the bracketted.

15 The critical value of (G_{ℓ}/R) is
given by

$$\left(\frac{G_{\ell}}{R} \right)_c = \frac{\Delta T (1 - k)}{k D} \quad (2)$$

20 where k is an equilibrium distribution coefficient,
 ΔT is a decrement of melting point due to the
impurity inclusion in melt and D is a diffusion
constant.

The impurity concentration c varies according to the equation

$$c = c_0 (1 - g)^{k-1} \quad (3)$$

where k is a distribution coefficient, g is a fraction solidified and c_0 is an initial impurity concentration in melt.

The effective distribution coefficient K_e is given by

$$K_e = \frac{k}{k + (1 - k) \exp(-R \delta / D)} \quad (4)$$

where δ is a thickness of solute boundary layer. In equilibrium the thickness δ is zero. Although the rising single crystal is rotated to equalize the thermal environment near the solid-liquid interface, the melt and solid near the interface have transient thermal fluctuations.

In the case of Czochralski method the thickness is given by

$$\delta (CZ) = 1.6 D^{1/3} \nu^{1/6} \omega^{-1/2} \quad (5)$$

where ν is a dynamical viscosity of melt and ω is a relative angular velocity between the crystal and the crucible.

The decrement of the melting point is

in proportion to the impurity concentration c in the melt. Then ΔT is written as

$$\Delta T = m c \quad (6)$$

where m is a constant multiplier.

5 From Inequality (1), Eq.(2), Eq.(3) and Eq.(6), the condition for occurrence of supercooling is given by

$$R > \frac{G_\ell k D (1 - g)^{1-k}}{K_e (1 - k) m c_0} \quad (7)$$

10 Hereafter the condition for occurrence of supercooling will be called as " supercooling condition " and the condition for non-occurrence of supercooling will be called as " non-supercooling condition " for simplicity.

15 If we assume $R \delta / D$ is much less enough than unity, the effective distribution coefficient K_e is nearly equal to the equilibrium distribution coefficient k . Using this approximation, Eq.(7) can be written as

$$R > \frac{G_\ell D (1 - g)^{1-k}}{(1 - k) m c_0} \quad (8)$$

20 In the case of LEC-growth of GaAs

$$\nu \cong 4 \times 10^{-3} \text{ cm}^2/\text{sec}$$

$$D \cong 1 \times 10^{-4} \text{ cm}^2/\text{sec}$$

The rotation speed ω depends on various factors. If we assume the rotation speed of the upper shaft is +2RPM and that of the lower shaft is -20RPM. The relative rotation speed becomes 22RPM. Then the angular velocity ω is calculated as

$$\omega = 2.3 / \text{sec}$$

Substituting these values into Eq.(5), we obtain

$$\delta = 0.02 \text{ cm}$$

If the pulling speed is 10 mm/H, the value of $R\delta/D$ is roughly estimated as

$$\frac{R\delta}{D} \cong 0.05$$

This is much less than unity. Therefore in the ordinary LEC method the effective distribution coefficient K_e can be replaced by the equilibrium distribution coefficient k in Eq.(4).

Then Inequality (8) is a supercooling condition.

The decrement of the melting point can be expressed in terms of gram equivalence N , because the gram equivalence N is in proportion to the concentration.

5 In the case of GaAs melt,

$$T = 360 N \quad (9)$$

This relation is independent of the kind of impurity. Here we will consider the GaAs melt doped with In. The weight percent of In in GaAs melt is denoted by " w ". The average atomic weight of GaAs is 72.3. The atomic weight of In is 114.82. Then the gram equivalence N is written as

$$N = 0.63 w \quad (10)$$

From Eq.(9) and Eq.(10), ΔT becomes

$$15 \quad \Delta T = 227 w \quad (11)$$

The weight percent w is given by an equation similar to Eq.(3), in which c_0 is replaced by an initial gram equivalence w_0 .

20 If we take w_0 and G_ℓ as explicit parameters, the supercooling condition is written as

$$R > \frac{Q G_\ell (1 - g)^{1-k}}{w_0} \quad (12)$$

where

$$Q = \frac{D}{227 (1 - k)} \quad (13)$$

The equilibrium distribution coefficient k of In in GaAs melt is approximately 0.1. The diffusion constant D was already given for In in GaAs melt. Using these values of k and D , the constant Q is calculated as

$$Q = 4.88 \times 10^{-7} \frac{\text{cm}^2}{\text{sec}^\circ\text{C}}$$

If we assume $G_\ell = 50^\circ\text{C}/\text{cm}$ and $w_0 = 0.015$ (1.5 wt%), the non-supercooling condition is given by

$$R \leq 1.62 \times 10^{-3} (1 - g)^{0.9} \text{ cm/sec} \quad (14)$$

For the pulling speed R , mm/H is more practical unit than cm/sec. In the practical unit of mm/H for R , the above condition is written as

$$R \leq 58 (1 - g)^{0.9} \text{ mm/H} \quad (15)$$

Till now we will consider the supercooling condition with a typical example. Inequality (15) shows that the upper limit of pulling speed R is determined by the fraction solidified g .

Although the fraction solidified has a definite physical meaning, g is not always an observable variable. Then under some assumption optimum change of the pulling speed R will be considered.

5 From Inequality (12), the non-supercooling condition is given by

$$R \leq \frac{Q G_\ell}{w_0} (1 - g)^{1-k} \quad (16)$$

Here the relation between the pulling time and the fraction solidified will be calculated.

10 The sectional area of a pulled single crystal, the density of the crystal and the initial weight of material melt are denoted by S , ρ and W respectively. If the single crystal is pulled up at a constant speed R_0 , the full length would be $W/\rho S$
15 at $g = 1$, in which all melt is solidified. The time required for pulling the single crystal is given by $W/\rho S R_0$.

Instead of a constant speed, we assume that the pulling speed R is changed as a function
20 of fraction solidified. For example, we assume the following equation

$$R = R_0 (1 - g)^{1-h} \quad (17)$$

where h is a constant of 0 to 1, and R_0 is an

initial pulling speed.

The fraction solidified g satisfies the equation

$$\frac{\rho S}{W} \int_0^t R dt = g \quad (18)$$

Differentiating Eq.(18) and substituting Eq.(17), we obtain a differential equation

$$\frac{\rho S R_0 (1 - g)^{1-h}}{W} = \frac{dg}{dt} \quad (19)$$

The solution is

$$(1 - g)^h = 1 - \frac{\rho S h R_0}{W} t \quad (20)$$

As mentioned before, h is a constant of 0 to 1. If h is equal to the upper limit 1 ($h = 1$), Eq.(20) would coincide with the ordinary pulling with a constant speed R_0 .

As the value h becomes smaller, the total time for pulling up the single crystal increases in inverse proportion to h .

Substituting Eq.(20) into Eq.(17), we obtain the pulling speed R as a function of time t ,

$$R = R_0 \left(1 - \frac{\rho S h R_0 t}{W} \right)^{\frac{1-h}{h}} \quad (21)$$

A purpose of the invention is to provide an LEC method in which the occurrence of impurity precipitation is effectively suppressed despite high impurity concentration.

5 Another purpose of the invention is to provide an LEC method in which total pulling time is not so long as one in a constant pulling without impurity precipitation.

The other purpose of the invention is
10 to provide an LEC method in which the occurrence of impurity precipitation is more effectively suppressed by heightening the temperature gradient in melt by a magnetic field.

Following is a description by way of example
15 only and with reference to the accompanying drawings of methods of carrying the invention into effect.

In the drawings : _____

FIG.1 is a graph showing the relations
between the pulling speed R and the fraction solidified g .

20 FIG.2 is a sectional view of an LEC apparatus for growing a single crystal.

FIG.3 is a graph showing the relations
between the pulling speed R and the pulling time t which
correspond to the curves depicted in FIG.1 under the
25 assumption of uniform diameter of single crystal.

The improvement of this invention relates to the pulling speed of the growing crystal.

Instead of the constant pulling speed this invention changes the pulling speed to avoid the
5 impurity precipitation.

FIG.1 demonstrates the relation between the pulling speed R and the fraction solidified g . The abscissa denotes the fraction solidified g . The left original point O corresponds to $g = 0$.
10 The right end point U corresponds to $g = 1$. The ordinate shows the pulling speed R . The supercooling condition provided by Inequality (12) or (16) is shown with a curve PU in the graph. Hereafter the curve PU is called " supercooling curve " (suffixed
15 with f) for simplicity. The hatched region above the curve f is a region where supercooling occurs.

Triangular region OPU below the supercooling curve f is the region where supercooling does not occur. It is desirable that the pulling speed
20 should be taken in the " non-supercooling region " OPU .

In conventional LEC methods, the pulling speed R is constant. R_0 denotes a constant pulling speed. Then the relation between R and g is simply shown by the straight line AC in FIG.1. The fraction
25 solidified at the point E is denoted by g_2 where the

straight line AC intersects the supercooling line f.
In the conventional methods where the fraction solidified g exceeds g_2 , the impurity precipitation happens.

Various pulling modes as a function of
5 g are thought to be possible. The pulling mode represented by Eq.(17) to Eq.(21) corresponds to the curve a connecting A and U.

FIG.2 is a sectional view of an LEC apparatus for growing a single crystal.

10 A crucible (1) is sustained by a susceptor (2). The susceptor (2) is supported by a lower shaft (3). The lower shaft (3) can rotate and go up and down.

The crucible (1) contains a melt (4)
15 of compound semiconductor and a liquid encapsulant (5) covering the melt (4). An inactive gas (6) pressurizes the liquid encapsulant (5) to prevent the element of group V from volatilizing out of the melt (4). Here "inactive gas" means nitrogen gas
20 or one of the inert gases - Ar, Ne, Kr, etc.

An upper shaft (7) can rotate and go up and down. A seed crystal (8) is fixed at the bottom end of the upper shaft (7).

A pressure vessel (10) encloses these
25

apparatuses. In this pressure vessel (10) the inactive gas can be pressurized at several atm to several tens atm.

5 A heater (11) is installed around the crucible (1). Another heater (12) is installed around the space above the crucible (1). The lower heater (11) melts the encapsulant material and the compound material, and keeps them in melting states. The upper heater (12) controls the cooling condition
10 of the single crystal pulled above the crucible (1). Both heaters (11) and (12) are carbon resistor heaters.

Magnets (13) mounted around the pressure vessel (10) generate a strong magnetic field in the
15 melt (4) in the crucible (1).

The action of the magnets (13) is to suppress the convection in the melt (4). In the melt some atoms are ionized. The ionized atoms feel the strong magnetic field generated by the magnets (13).
20 Lorentz's forces caused by the magnetic field suppress the free motions of the ionized atoms. The ionized atoms are bound along magnetic field lines, which results in braking the convection of melt (4).

5 The application of magnetic field to melt in LEC method has been already proposed. The action of the applied magnetic field is to prevent turbulences in melt and supress the perturbation of the solid-liquid interface by braking the convection.

10 In this invention the magnetic field plays another role instead of reducing EPD. The magnetic field raises the temperature gradient G_ℓ in melt and suppresses the temperature change of the melt near the solid-liquid interface by weakening the convection. If G_ℓ is raised, the supercooling curve f is displaced upward in FIG.1. The upward displacement of the supercooling curve f extends the region of non-super-cooling. The effects that the magnetic field
15 yields upon the temperature change will be explained.

Even if the pulling speed R is constant, time derivative of the height of an arbitrary point of a single crystal measured from the solid-liquid interface is not always equal to the constant R , because
20 the height of the solid-liquid interface itself changes. This is the reason why the striations happen. Striation is one of crystal defects. Striped patterns appear on an etched surface of a crystal. This corresponds to the fluctuation of
25 growing speed.

We think that there are two reasons why the fluctuation of the level of the solid-liquid interface occurs. One is the fluctuation of the temperature T_b in time near the solid-liquid interface due to the changes of heater power and the convection mode in melt. This temperature fluctuation is written as $T_b(t)$.

Another reason is the temperature difference of the single crystal along the circular direction near the solid-liquid interface. Temperature differences in a crystal can be thought along three directions — radial direction, circular direction and axial direction.

The axial temperature difference does not have a significant effect on the occurrence of striation, because a crystal does not go upward so fast as the axial temperature difference might cause rapid temperature fluctuation. The radial temperature difference also plays a minor role for the occurrence of striation, because heat transfer along a radial direction is quite slow.

Then circular temperature difference is quickly transmitted by the relative rotation of the crystal against the crucible. The circular temperature difference can be analyzed into many harmonic

modes. Although higher modes may occur, the lowest mode (first mode) of circular temperature difference is most important, because the lowest mode gives largest temperature difference.

5 The temperature change of an arbitrary point along the circumference is written as $\Delta T_a \sin \omega t$ in the lowest mode where ΔT_a is the amplitude and ω is the angular velocity.

10 After all, the time fluctuation of temperature near the solid-liquid interface is given by

$$\frac{\partial}{\partial t} (T_b(t) + \Delta T_a \sin \omega t) \quad (22)$$

15 The height of a single crystal measured from the solid-liquid interface increases roughly in proportion to the constant pulling speed R_0 . However if the temperature fluctuations exist near the solid-liquid interface, the increasing rate of the height is perturbed by the fluctuations.

20 The solid-liquid interface is an isothermal surface. A unit temperature difference causes the level change of the solid-liquid interface by $1/G_\ell$, where G_ℓ is the temperature gradient in melt.

25 Then the effective pulling speed $R(t)$ with fluctuation is given by

$$R(t) = R_0 - \frac{1}{G_\ell} \frac{\partial}{\partial t} [T_b(t) + \Delta T_a \sin \omega t] \quad (23)$$

where the first term R_0 is the constant pulling speed and the second term is the fluctuation of pulling speed due to the temperature fluctuations. Eq.(23)

5 is written as

$$R(t) = R_0 \left(1 - \beta \cos \omega t - \alpha \frac{\partial T_b(t)}{\partial t} \right) \quad (24)$$

where β is called " rotation striation coefficient " and α is called " non-rotation striation coefficient ". They are defined by

$$10 \quad \beta = \frac{\omega \Delta T_a}{R_0 G_\ell} \quad (25)$$

$$\alpha = \frac{1}{R_0 G_\ell} \quad (26)$$

For a rough estimation of the coefficients, we assume the parameters as follows, for example

$$15 \quad R_0 = 2.78 \times 10^{-4} \text{ cm/sec} \quad (27)$$

(equal to 10 mm/H)

$$G_\ell = 50^\circ\text{C/cm} \quad (28)$$

$$\omega = 2.3 \text{ rad/sec} \quad (29)$$

(equal to 22 RPM)

Then

$$20 \quad \beta = 165.8 \Delta T_a \quad (30)$$

$$\alpha = 71.9$$

This estimation shows us that the striation coefficients are large values in comparison with 1. Because of the large striation coefficients α and β , the effective pulling speed $R(t)$ is not a value similar to R_0 . $R(t)$ can take a value a hundred times as large as R_0 . For example, if $\partial T_b / \partial t$ is assumed to be $1^\circ\text{C}/\text{sec}$, $R(t)$ becomes about seventy times as large as R_0 .

If a magnetic field is applied, the convection in the melt is weakened. The surface state of the melt becomes more stable and the fluctuation of the temperature near the solid-liquid interface becomes smaller, which result in the reduction of $(\partial T_b / \partial t)$.

If the effective pulling speed $R(t)$ exceeds the supercooling curve f even for a short time, the supercooling will occur. Because $(\partial T_b / \partial t)$ is a fluctuation term whose time average is zero, the supercooling condition is quickly replaced by the non-supercooling condition. If the time derivative $(\partial T_b / \partial t)$ is large, transitions between the supercooling state and the non-supercooling state will occur at high frequency, which leads to the generation of striations in the pulled single crystal.

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Hence the application of magnetic field prevents the occurrence of striations by reducing the fluctuation of T_b and suppressing the supercooling.

5 However magnetic field is not an essential requirement of this invention. This invention enables us to dispense with the magnetic field.

In the conventional method, which is not novel by itself, the single crystal is pulled up by rotating the lower shaft (3) and the upper shaft (7) from the melt (4) with a relative pulling speed R.

10 Instead of the constant speed, this invention changes the pulling speed.

The novel feature of this invention is to propose the time dependent pulling speed in LEC methods.

15 The upper limit of the pulling speed is determined by the supercooling condition. In the conventional LEC methods the probability of supercooling has been neglected. The upper limit of the pulling speed was determined from the viewpoint to reduce EPD.

20 As mentioned previously, EPD is the etch pit density appearing on wafers. The etch pits correspond to dislocations. The wafers made by LEC methods have high dislocation densities in general.

There are several reasons why dislocations are generated. One reason is the quick cooling of a single crystal which causes thermal stresses. To delay the cooling and to reduce the temperature gradient, the pulling speed R should be small.

Therefore conventional methods has adopted the constant pulling speed R_0 .

As shown in FIG.1, the constant pulling speed R_0 exists below the supercooling point R at $g = 0$ and the line A - C of the constant pulling speed intersects the supercooling curve f .

The curves which show the relation between the fraction solidified g and pulling speed R is called a " pulling speed curve ". From the standpoint of avoiding the occurrence of supercooling, the pulling speed curve $R(g)$ should be taken an arbitrary single-valued function contained in the triangular region OPU in FIG.1.

However the upper limit of the pulling speed is determined by another ground such as EPD other than supercooling.

The initial pulling speed is determined by the same reason in this invention. Thus the initial pulling speed of this invention assumed to be R_0 .

Conventional pulling speed curve is the direct line A - C suffixed with e, which reaches to the supercooling condition at the point E where impurity precipitation begins. The part of crystal with the fraction solidified of g_1 to 1 cannot be used as substrates of electronic devices.

This inventor was aware of the importance to avoid supercooling for the first time. The main purpose of this invention is to provide appropriate pulling speed curve or function as a function of fraction solidified g or pulling time t .

Any pulling curves which start from the point A and decrease monotonously regarding t are available. Such pulling curves reach to the supercooling condition later than g_2 , which results in the delay of the occurrence of impurity precipitation. Thus these improved pulling curve enables us to make a single crystal which has an available part more than ones made by conventional LEC methods.

Four typical pulling curves a, b, c and d allowed by this invention are shown in FIG.1.

The pulling curve a connecting smoothly the initial point A to the final point U corresponds to Eq.(17) or Eq.(21).

If h is determined to be equal to k , the pulling curve a will be equal to the curve obtained by moving the supercooling curve toward the ordinate.

5 In FIG.1 the supercooling curve f is explicitly depicted, because it is assumed that the curve is predetermined. However the supercooling curve f is not necessarily known well.

10 The supercooling condition includes the phenomenological parameters k , D and G_ℓ . The distribution coefficient k and the diffusion constant D are the parameters depending on the temperature and the pressure. And they cannot be measured easily. Some measured values were reported.

15 There is a more difficult problem in determining the supercooling curve. The supercooling condition includes the temperature gradient G_ℓ in melt. This value is not always a known-parameter nor a controllable one.

20 Even if we can control the output powers of the heater (11) and (12) as well as the rotation speeds of the upper shaft (7) and the lower shaft (3), we cannot always control the temperature gradient G_ℓ .

In these cases the simple way to determine an appropriate pulling curve which starts from the

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initial point A and reach to the final point U without intersecting the supercooling curve f is to choose a typical curve a with h less than or equal to k.

5 The pulling curve a never intersects the supercooling curve f, because the initial point A is below the point P and the parameter h is less than or equal to k.

10 However the pulling curve a has a disadvantage that is takes much time to pull up a whole single crystal. This disadvantage will be more easily understood by showing the curve in time-speed coordinates.

FIG.3 is a graph showing the relations between the pulling speed R and the pulling time.

15 The curve a in FIG.3 corresponds to the curve a in FIG.1. This curve a signifies Eq.(21). Eq.(20) shows that the pulling speed becomes very small as the fraction solidified g approaches to 1. Thus the curve a has a long tail in FIG.3. Total
20 pulling time t_a is very long.

The line AC in FIG.3 shows a conventional pulling speed. The total pulling time t_e is denoted by the length AC, which is equal to $W/(\rho S R_0)$. However the improved method will take $W/(\rho S R_0 h)$
25 to pull up a single crystal with a full length, because the pulling speed approaches nearly to zero

in the vicinity of $g = 1$. Even if the pulling operation would be ceased at a fraction solidified of 0.8 to 0.9 in practice, it would require much long time. The pulling curve a with $h = 0.1$ will take ten
5 times as long as the time t_e of the constant pulling e.

Most ideal pulling speed program will be given by the curve d characterized by the points A, D and U in FIG.1. Between the point A and the point D the pulling speed is constant ($R = R_0$).

10 The partial curve between the point D and the point U is determined by a equation similar to Eq.(17). This equation is obtained by replacing R_0 in Eq.(17) by $R_0 / (1 - g_d)^{1-h}$, where g_d is the fraction solidified at the point D.

15 The time-speed curve d is shown in FIG.3. The curve d consists of the straight line AD and the monotonously decreasing curve D t_d .

The pulling speed R falls quickly from the point D. Although the partial curve from D to t_d has
20 a long tail, the total pulling time t_d is much shorter than t_a . In the case of the curve d the most important point is to determine the turning point D.

To avoid the occurrence of supercooling, the whole curve d must lie below the supercooling curve f.
25 If the supercooling curve f is a known curve, it is easy to determine the appropriate turning point D.

It is rather difficult to determine a pertinent turning point D, because in many cases the supercooling curve f is an unknown curve.

5 In these cases smooth curves without a turning point at which the pulling speed R changes suddenly are more preferable than the curve d. The pulling curve c shows such an example without turning points. The pulling curve c starts from the common initial point A and decreases slowly with t. The whole
10 pulling curve c lies below the supercooling curve f. However the total pulling time t_c is longer than t_d . The pulling curves a, b, and c demonstrated till now give pulling speed programs immune from supercooling. These typical pulling curves converge to
15 0 at the limit of $g = 1$.

However they have a common disadvantage that very long pulling time is required, because the pulling speeds become slow in the vicinity of $g = 1$.

Another most practical way be given by
20 the pulling curve b in FIG.1. The pulling curve b does not converge to the point U at $g = 1$. It takes an definite positive value of R at $g = 1$. The curve b in FIG.3 show the time dependence of R. The total pulling time is t_b . Even at $t = t_b$ the pulling speed is not
25 zero. This curtails the total pulling time.

The total pulling time t_b is shorter than t_a , t_c or t_d .

Although the pulling curve b separates from the straight line A - C and begins decreasing earlier than the curve c or d, the pulling curve b will finish earlier than the curve c or d.

If the curve b is raised higher near the curve c, the total pulling time t_b would be more shorter.

At the point B the pulling curve b intersects the supercooling curve f. " g_1 " is the fraction solidified at the point B. After the intersection, the impurity precipitation will occur. The tail part of a pulled single crystal from $g = g_1$ to $g = 1$ cannot be used as substrates for electronic devices because of the impurity precipitation.

The fraction solidified g at which a pulling curves intersects the supercooling curve is called "critical fraction solidified" of the pulling curve. The critical fraction solidified of the conventional pulling curve is g_2 . The critical fraction solidified of the curve b is g_1 . Since the curve b always exists below the conventional pulling e, g_1 is larger than g_2 . The part of the crystal with the fraction solidified between g_2 and g_1 becomes good single crystal for the substrates.

Another pulling speed curve similar to the curve b is also possible. Those curves lower the pulling speed R in accordance with the curve b till a certain time and then the pulling speed is kept to be constant. Thus the pulling speed curve consists of a
5 monotonously decreasing curve and a straight line.

This variation of the pulling curve b is based on the consideration that it is insignificant to continue lowering the pulling speed after the
10 point B, because supercooling has already happened at the point B. It is more useful to keep the pulling speed constant after the point B. This curtails the pulling time.

But in practice the point B at which supercooling occurs is not always known prior to the pulling
15 of a single crystal.

Thus the pulling speed is kept to be constant after some pertinent time.

Embodiments of the invention will be
20 explained.

(1) A GaAs single crystal of two inches in diameter was pulled up from 1.5 kg of a GaAs melt including $5.5 \times 10^{20} \text{ cm}^{-3}$ of In by this invention. The melt was covered with B_2O_3 melt - liquid
25 encapsulant.

Initial pulling speed was 10 mm/H. The pulling speed was continuously reduced from 10 mm/H to 3 mm/H. Then the pulling speed was kept to be 3 mm/H till the end of the pulling.

5 In concentration was $5.5 \times 10^{19} \text{ cm}^{-3}$ at the top portion of the pulled single crystal.

 No In precipitation exists from the top portion to the portion with $g = 0.62$ (namely the partial weight of the crystal from the top portion to this portion was 930 g). Furthermore whole of
10 these portions from $g = 0$ to $g = 0.62$ was a single crystal without twins or polycrystallization.

 To compare this result with the conventional LEC method, the another GaAs crystal was
15 pulled from the same melt with a constant pulling speed. The pulling speed was 10 mm/H from the beginning to the end. The pulled crystal was single-crystallized and free from impurity precipitation between $g = 0$ and $g = 0.37$ (the
20 partial weight was 555 g).

 This improvement enabled us to obtain an additional 375 g of good single crystal.

(2) Under the application of a static magnetic field a GaAs single crystal was pulled
25 from the In-doped GaAs melt according to this

invention. All conditions other than the magnetic field are same as the embodiment (1), The pulling speed R was lowered from 10 mm/H to 3 mm/H.

5 Then the 3 mm/H of pulling speed was kept till the end of the crystal growth.

The strength of the applied magnetic field was 1800 Oe at the center of the melt. The direction of the magnetic field was vertical at the melt center.

10 The crystal grown by the improved method was single-crystallized and free from impurity precipitation from $g = 0$ to $g = 0.75$ (the partial weight of the good crystal is 1125 g).

15 To estimate the effect of the change of the pulling speed, the another In-doped single crystal was pulled under the same magnetic field at the constant pulling speed. The pulling speed was 10 mm/H from the beginning to the end. The crystal pulled with the constant speed was free from impurity
20 precipitation between $g = 0$ and $g = 0.54$ (the partial weight of the good crystal is 810 g).

Table 1 shows the upper limits of the good crystal part which is free from impurity precipitation.

25

Table 1 FRACTION SOLIDIFIED OF GOOD
CRYSTAL PART

	EMBODIMENTS 10mm/H 3mm/H decreasing pulling speed	CONVENTIONAL WAYS 10mm/H constant pulling speed
NO MAGNETIC FIELD	0.62	0.37
1800 Oe of MAGNETIC FIELD	0.75	0.54

These results verify the consideration of
this Inventors that the impurity precipitation would
be generated by the occurrence of supercooling, and
suppression of supercooling is effective to avoid
5 the impurity precipitation.

This Inventors think anybody other than
the Inventors has not noticed the relation between
the impurity precipitation and the supercooling till
now.

10 The advantages of this invention will be
now explained.

(1) Because the pulling speed is lowering so slowly as to avoid the occurrence of supercooling, the impurity precipitation scarcely occurs. Highly impurity doped single crystals without
5 impurity precipitation can be obtained with a high yield.

(2) This improvement given by this invention is only to lower the pulling speed slowly during the crystal growth. It is easy to put the improve-
10 ment into practice.

Although the pulling time becomes longer, this improvement can be practised without additional cost except the cost owing to the extension of the pulling time.

15 (3) Application of magnetic field will raise the effect of this invention. Lorentz's force of the magnetic field heightens the temperature gradient G_ℓ in melt by braking the convection of melt.

20 Enhanced temperature gradient G_ℓ raises the supercooling curve in the R-g graph. Upward displacement of the supercooling curve suppresses the occurrence of impurity precipitation.

(4) This invention has a wide scope of
25 applications. Highly impurity doped single crystals

of compound semiconductors of groups III-V such as GaAs, InP, InAs, GaP, InSb, GaSb etc., can be made by the LEC methods improved by this invention. The impurities to be doped are any elements such as In, B, Sb, Si, Ga, As and P other than the host elements.

5

- (5) This invention is especially useful at high impurity concentrations, because supercooling is inclined to occur under the dense existence of impurity atoms. For example, preferable impurity concentration is about $5 \times 10^{18} \text{ cm}^{-3}$ to $8 \times 10^{19} \text{ cm}^{-3}$ at the top portion of the pulled GaAs crystal.

10

CLAIMS

1. A method for growing a single crystal
of compound semiconductor comprising ; melting a
liquid encapsulant material and compound semi-
5 conductor material doped with one or more than
one impurities which have a distribution coefficient
less than 1 and are selected from In, B, Sb, Si,
Ga, As, or P, dipping a seed crystal into the
material melt covered with the liquid encapsulant,
10 and growing a single crystal from the melt by
pulling up and rotating the seed crystal ;
characterized in that the pulling speed R is lowered
during the crystal growth.
2. A method for growing a single crystal as
15 calimed in claim 1, characterized in that the melt
is a GaAs melt, the doped impurity is In or B and the
impurity concentration at the top portion of the
pulled crystal is $5 \times 10^{18} \text{ cm}^{-3}$ to $8 \times 10^{19} \text{ cm}^{-3}$.
3. A method for growing a single crystal as
20 claimed in claim 1, characterized in that the initial
pulling speed is 4 to 15 mm/H, the final pulling
speed is 1 to 5 mm/H and the pulling speed is slowly
lowering from the initial speed to the final speed.

4. A method for growing a single crystal as claimed in claim 1, characterized in that as a function of fraction solidified g , the pulling speed R is given by

5
$$R = R_0 (1 - g)^{1-h}$$

where R_0 is an initial pulling speed, h is a positive constant less than 1 and g is a fraction solidified which is a quotient of the weight of the solidified part divided by the initial weight of melt.

- 10 5. A method for growing a single crystal as claimed in claim 1, characterized in that the pulling speed R is kept to be constant R_0 till a turning point, starts decreasing at the turning point, and converges to 0 near the end.
- 15 6. A method for growing a single crystal as claimed in claim 1, characterized in that a magnetic field is applied in the melt during the growth.

FIG. 1

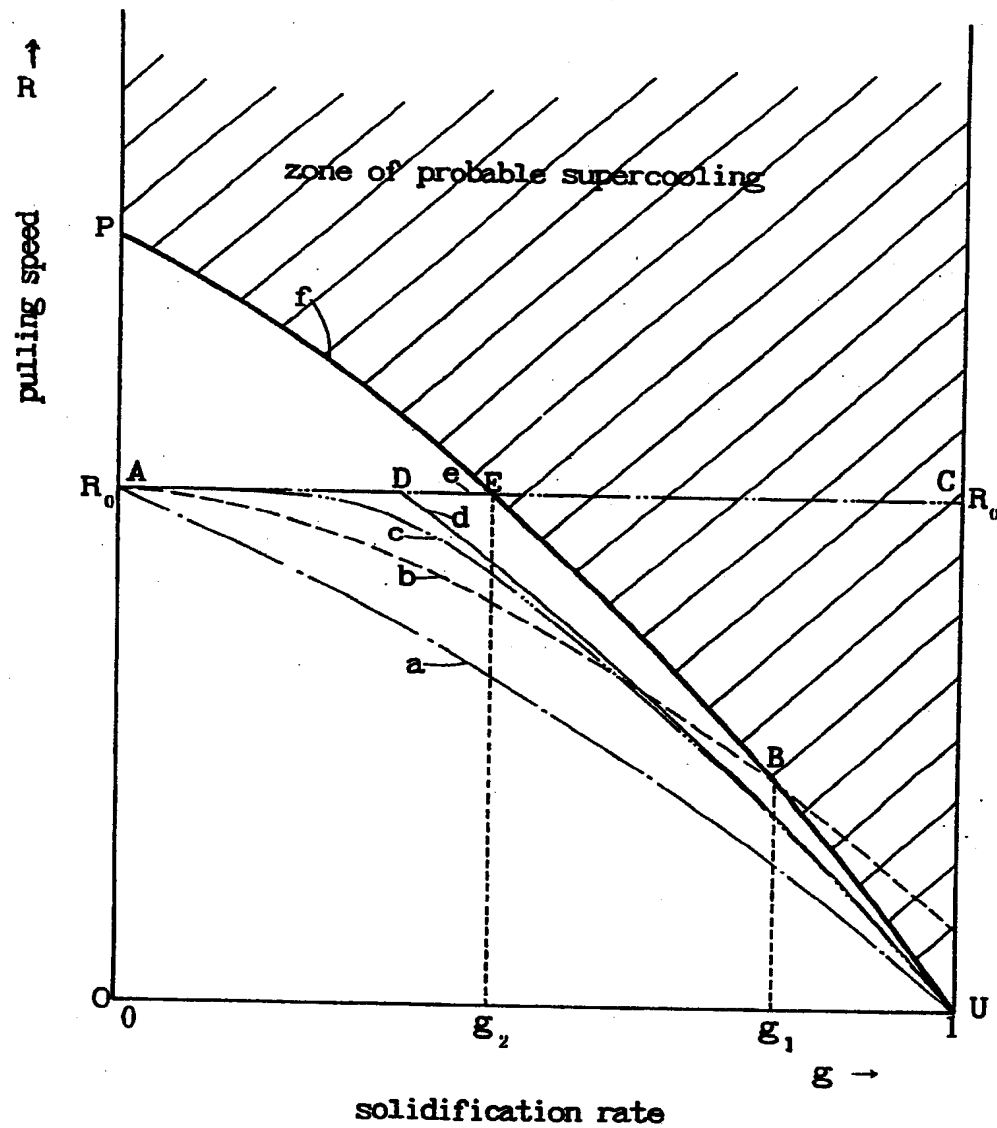


FIG. 3

